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REQUIREMENTS FOR DIGITAL COMPUTER SIMULATION OF GAS TURBINE PROPULSION SYSTEM PERFORMANCE PHASE I

STEADY-STATE AND TRANSIENT ENGINE PERFORMANCE SIMULATION

Lex Hutcheson, W. C. Armstrong, and C. B. Cooper

ARO, Inc.

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ENGINE TEST FACILITY

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NOTICES

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FOREWORD

The study reported herein was sponsored by the Air Force Aero Propulsion Laboratory (AFAPL), Air Force Systems Command (AFSC), Wright-Patterson Air Force Base, Ohio, under Program Element 62203F, Project 3066.

The results of the study were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under contract F40600-71-C-0002. The study was conducted in the Engine Test Facility (ETF) in coordination with Central Computer Operations (CCO) from July 15, 1969, to June 30, 1970, under ARO Project No. RW5003, and the manuscript was submitted for publication on November 16, 1970.

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This technical report has been reviewed and is approved.

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ABSTRACT

Present and near-future requirements for the addition of digital computer simulation of gas turbine engine steady-state and transient performance to the present Engine Test Facility and Propulsion Wind Tunnel Facility digital data capability were determined based on information and guidance provided by the Air Force Aero Propulsion Laboratory and various gas turbine engine manufacturers. During Phase I of this study, digital computer high-speed core memory size and throughput times were determined and are presented for several modern steady-state and transient mathematical model simulation programs. Display requirements were also determined and are presented for full utilization of the mathematical model results, off-line and on-line. Some preliminary results on dynamic compressor mathematical models are discussed.

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SECTION I
INTRODUCTION

1.1 BACKGROUND

During the past five years, an ever-increasing amount of work has been done by the Air Force Aero Propulsion Laboratory (AFAPL) and the various gas turbine engine manufacturers toward obtaining a more precise understanding of the basic mechanisms of turbo-propulsion systems. The underlying cause of this increased effort has been the severe requirements imposed by aircraft weapons systems designs which push the state-of-the-art in many areas. System tolerances are no longer great enough to absorb even slight deficiencies in any one component of the system.

The effort has expanded in two directions: (1) basic research, design, and detailed testing and development of the various components which go into a system to obtain more precise information about the performance of each component, and (2) systems engineering, design, and testing of the integrated components to better quantize the performance of the total system for mission planning requirements.

At the same time, significant developments have taken place in adjacent areas of technology which have greatly benefited the aircraft weapons system efforts. A major improvement has been the development of user-oriented digital computer systems with large-scale high-speed memories. Input/output methods and speeds have been greatly improved, and now it is practical to interface design and analysis engineers with large computers using fully interactive graphics terminal capabilities.

The development of mathematical models of gas turbine propulsion systems was necessitated by the requirement to define precisely system performance, and the application of these models was made possible by the development of advanced digital computer systems. The models developed for customer use have grown from early stages of gross overall engine performance definition to precise and comprehensive simulations which give the entire engine parameter definition, both internal and overall. The present gas turbine engine math models contain detailed performance estimates for the fan, compressor, burner, turbine, augmenter, exhaust system, and engine controls (Fig. 1, Appendix). The utility of these math model programs has advanced to such a point that now the Air Force requests math models to be supplied with each proposal and to be used continuously throughout the engine

and inlet development cycle with continuous up-dating, comparing testing results as obtained, through the Preliminary Flight Rating Test (PFRT) and Military Qualification Test (MQT) of the propulsion system. A requirement for steady-state and transient math models is written into the contracts for both the F-15 and B-1 aircraft.

Many gas turbine engine development and qualification tests are conducted at AEDC for the Department of Defense and engine contractors. To perform the assigned mission in an efficient and productive manner, it is necessary for AEDC to have access to the latest and best information about the expected engine performance, and this information must be available on-line, during actual testing for optimum spacing of test points and cross-correlation of test results and pretest performance predictions. Another important objective is the reduction or elimination of large volumes of test data except for that which deviates from normal or anticipated results.

1.2 OBJECTIVES

The objective of this investigation is to provide preliminary criteria to permit the formulation of specifications for the automatic data processing equipment required for full utilization of computer simulation of gas turbine propulsion system performance. A study of the existing engine computer models, as well as those proposed to be supplied under new engine development contracts, was made to establish the digital computer memory size and speed requirements for off-line processing at predetermined engine operating conditions. The off-line capability may then be augmented to provide for on-line input of environmental test conditions so that off-line operation of the math models will be possible at the as-tested conditions. This capability may be further augmented to provide for on-line, near-real-time operation with remote display of results of the math models at the as-tested conditions. A further step in capability will permit on-line comparison of engine test data with the expected performance from the math models operating in a side-by-side, on-line mode.

Calculated engine performance from math model computer programs when used in conjunction with the AEDC propulsion engine test cells and propulsion wind tunnels equipped with reliable, highly accurate, on-line data acquisition and processing systems will provide for maximum testing effectiveness and at the same time require that only the minimum number of tests be performed. The minimum number of tests will be possible because data acquisition in regions where test engine performance agrees with the expected returns from the math model can be

reduced. The maximum testing effectiveness will be possible because test observations may be spaced in an optimum manner in regions where test engine performance differs with the expected returns from the math model computer program.

SECTION II
DESCRIPTION OF GAS TURBINE ENGINE MATHEMATICAL MODELS

Mathematical models of gas turbine engines programmed for use on large high-speed digital computers are now being used extensively by engine and airframe manufacturers, Department of Defense (DOD) technical evaluation agencies such as the AFAPL, and testing agencies such as the AEDC. These programs may be generally categorized (Fig. 2) into engine steady-state, transient, and dynamic performance simulation models, and inlet/engine combined math models.

2.1 STEADY-STATE ENGINE MATH MODELS

Steady-state engine performance simulation programs for use on large-scale digital computers were the earliest models generated. The steady-state programs which were first prepared for customer use were computerized tables of overall gross engine performance as reported in the cumbersome engine specification manuals. Later some manufacturers included gross performance relationships in the form of gas generator curves, but many customers decks have now evolved to completely responsive, cycle-matching programs.

2.1.1 Table Look-Up Model

The table look-up programs merely speed up and automate the tedious process of obtaining engine performance predictions and applying the numerous correction factors as presented in the engine specification manual. Performance parameters include only overall gross effects with very few, if any, internal parameters (which are greatly needed in any engine development test). Therefore, these table look-up programs were useful only for defining the "target" or design specification performance of the engine, and these programs did not supply any diagnostic information when the program did not compute. The tables contained in this type of program are usually produced using a cycle-matching program which is discussed below. Many versions of this type of program are still being used today, and one representative program of this type was examined during the present investigation.

2.1.2 Gas Generator Curve Models

The second type of engine math model computer program developed was the temperature rise, gas-generator, or heat addition program. This program may use the table look-up method of curves for fan/compressor, turbine, and exhaust system performance and then perform the calculation of gross engine performance by entering predetermined gas-generator curves at the proper values of burner inlet temperature, fuel/air ratio, engine pressure ratio, etc. Again, this method does not produce all internal engine performance parameters which completely define the cycle and are fully responsive to the testing or flight environment as the actual engine must by nature be. Two representative programs of this type were examined during the present investigation.

2.1.3 Cycle-matching Models

The most recent type of customer steady-state math model computer program is the engine cycle-matching model which includes precise mathematical models of each engine component (Fig. 3) integrated into one computer program which iterates a solution for each engine component until the complete cycle is matched or balanced. In this type of program, the performance prediction curves of any component or combination of components may be changed, and the effect on the performance estimates of the other components observed, since all internal engine parameters are necessarily available. This type of math model is first used extensively by the turbine engine manufacturers in performing engine cycle component design studies to help determine the engine component geometries necessary to produce the desired, or specified engine performance. The second phase in the development of the cycle-matching math model program is the production of a specification program which includes estimates of the performance of realistic engine components which will produce the desired, or specified, engine performance. Finally, the cycle-matching math model program accurately reflects a present state of the engine, whether it be preliminary design, initial development, development, or rated. This program form is particularly useful for pretest performance estimation and on-line test comparison during any phase of an engine environmental ground testing program, or flight test program. Several math models of this type have been extensively used and studied during this investigation.

2.1.4 Cycle-Matching Balance Techniques

The computer throughput time for a selected cycle-matching problem required, until recently, several minutes to complete since

each individual engine component performance estimate was computed for a given set of component inlet parameters, which depended on the exit parameters of the preceding component. As the performance estimate of each component was determined, the performance estimates for the preceding components had to be recalculated in a "nested-loop" fashion to include the effects of the added component, and so forth, until the entire engine cycle was completely balanced from fan inlet to exhaust system exit. This process usually required many iteration loops and execution times on the order of several minutes on second-generation digital computers.

To use the cycle-matching technique, the nonlinear, ordinary differential equations describing the engine performance are written in finite difference form. The resulting set of nonlinear algebraic equations is then solved simultaneously by the modified Newton-Raphson method. This method was applied to the gas turbine engine math model cycle matching programs almost simultaneously by the AFAPL Simulation of Turbofan Engine (SMOTE) balance technique (Ref. 1) and by the major gas turbine engine manufacturers (Refs. 2 and 3). To solve a cycle match problem, an initial estimate of the operating point of the engine cycle is made by the computer program using predetermined estimates or estimate routines. If the initial estimate is sufficiently far from the proper balanced cycle point corresponding to engine power and flight condition, the SMOTE matrix solution is invalid because of the nonlinearity of the system; therefore, a new set of initial estimates, moved in the direction of convergence, is calculated, and the SMOTE matrix parameters are regenerated. This process normally requires only a few trials before cycle balance is achieved and thus reduces the problem execution time by as much as two orders of magnitude, from several minutes to a few seconds. Diagrams illustrating the "nested-loop" and SMOTE balance techniques are shown in Fig. 4.

2.2 TRANSIENT ENGINE MATH MODELS

Gas turbine engine transient math model computer programs had a different beginning from the steady-state models. Transient models were developed during the design of engine control systems with analog computer simulations which attempted to duplicate the mechanism of the engine controls. Later, approximations were added for the other engine components in order to qualitatively determine the estimated interactions of the engine and a particular control system. When more accurate results were demanded from transient simulations, some manufacturers went to hybrid computer systems where the component data tables and curves were stored and manipulated by a digital computer

coupled to the analog system which performed the integrations required by the programmed controls responses. However, it was soon evident that, with the introduction of very fast digital computers using analog simulation software such as DSL90, DYNASOAR, CSMP, and SPADE (Ref. 3), all-digital programs were a necessity in order to allow any kind of math model program interchange between the engine manufacturers, DOD agencies, and testing facilities. Today all-digital transient math model performance simulation programs are used almost universally for gas turbine engine transient performance simulation, except for specialized "in-house" controls design studies where the analog and hybrid systems may be more economically employed.

Most engine transient math model digital programs now have, generally, all the information that is contained in the steady-state math model programs, with time as an added independent variable, so that all engine performance estimates are computed as a function of flight condition, engine power, and time. The same mathematical iteration techniques are employed as with the steady-state math model programs, with the exceptions that flight condition and engine power may vary functionally with time, and initial estimates are incremented and not maintained during non-steady-state operation. Consequently, program convergence requires less time after the initial transient starting point (steady-state) has been balanced. Methods to account for realistic physical phenomena within the engine cycle include temperature lags to account for temperature transients in the various engine component masses, volume dynamics using mass flow difference integrations to account for flow transients due to mass storage particularly through the fan and compressor components, and torque difference integrations to account for shaft speed transients due to mass inertia.

The execution times of these programs vary significantly with the specified time increment (t_c) used for integration and with internal computer speed. For a typical calculation time increment of 0.01 sec, the execution is approximately 10 sec for each second of real simulation time for the IBM 360/75 computer. Several engine transient models were used and studied during this investigation.

One customer program (AIDES, Ref. 4) obtained and used during this investigation combines both steady-state and transient engine math model simulations into one computer program where the option was made available to compute transient performance or only steady-state performance in single or multiple cases.

2.3 DYNAMIC MATH MODELS

Fan/compressor dynamic math model digital programs which may be responsive to aerodynamic input fluctuations in the 0- to 1000-Hz range of frequencies have been developed only recently. One such model studied during the present investigation is from the set of dynamic models developed under the Air Force Propulsion System Flow Stability Program (Contract No. F33615-67-C-1848) for prediction of compressor response to spatial and time-variant distortion (Ref. 5). A fan/compressor dynamic model may simulate the engine geometry on a stage-by-stage and row-by-row basis and thus become even more complex and computer time-consuming than a total-engine simulation for the steady-state or transient cycle-matching math models.

Dynamic math models may be used to predict fan or compressor stall limits and speed/flow relationship changes. Dynamic (and transient) models may also be constructed to simulate inlet performance and mated with engine transient math model computer programs to help predict inlet/engine coupling characteristics.

The dynamic models discussed in Ref. 5 simulate compressor stage-by-stage characteristics using stage characteristic curves for efficiency, temperature rise, and pressure rise. In constructing the model, the assumption is made that compressor stage may be viewed as an "actuator disc" which accomplishes the momentum exchanges necessary for temperature rise and pressure rise, plus a "lumped volume" wherein mass is stored temporarily to account for the stage flow decrement or increment required to satisfy the momentum energy and continuity equations. Dynamic math models will be further investigated during Phase II of this program.

2.4 INLET/ENGINE MATH MODELS

The problems associated with the integration of inlet and engine to form a workable aircraft propulsion system is a much publicized subject recently with the advent of supersonic high performance aircraft systems (Ref. 6). The simulation of the entire propulsion system with computerized mathematical models (Refs. 7 and 8) is being done for modern aircraft systems such as the F-15 air superiority fighter.

The published math model papers discuss integrated simulations of supersonic inlets with gas turbine engines, including both inlet and engine controls. These math models must be classified as transient simulations under the previous definitions given for engine math models.

Computer memory size and speed requirements to run these math models on-line at AEDC during full-scale inlet-engine integration tests will be determined during Phase II of this study.

SECTION III
DIGITAL COMPUTER REQUIREMENTS FOR ENGINE STEADY-STATE AND TRANSIENT PERFORMANCE SIMULATION

Computer requirements for the digital simulation of gas turbine engine performance have been determined for engine steady-state and transient math models. Further study is being conducted to investigate the computer requirements for digital simulation of engine dynamic and combined inlet/engine math models.

Before defining the specific digital computer requirements for on-line engine simulation using math models, it was necessary to determine the proper location of the digital math model results and to make comparisons within the AEDC Engine Test Facility (ETF) and Propulsion Wind Tunnel Facility (PWT) on-line digital data flow scheme (Fig. 5). In order to take full advantage of this added capability, and at the same time, to maintain the proved integrity of the present on-line capability, this step was mandatory. The present on-line data acquisition systems at ETF and PWT utilize Raytheon 520 computers with 32,000 and 20,000 words, respectively, of core memory and additional disc and drum system storage capability. The maximum acceptable delay time between the test control room signal to initiate data acquisition and data scan initiation and computation is 10 sec. The flow of all three types of test data (steady-state, transient, and dynamic) from recording, digitizing, and calibration to engineering unit and performance calculations and finally to mass data storage and on-line display for engineering review is shown in Fig. 5. Since the math models require some engineering unit and performance calculation results for input, the math models must be placed in the on-line data flow stream at the point where these values are available. Comparison ratios or differences must be computed immediately thereafter, as illustrated schematically in Fig. 5.

To determine the digital computer requirements for the addition of math models to the present ETF and PWT on-line digital data capability, a target data turnaround time was established to specify the approximate time required for each major operation between the initiation of data acquisition and the on-line display of complete results for engineering review. The critical events in the ETF and PWT on-line digital data flow and the associated time requirements to meet the

overall target turnaround time of approximately 5 min are shown in Fig. 6. To add the math model results to the present on-line capability requires a math model throughput time of 1 min, or less, and sufficient core memory to perform the computation simultaneously with the actual performance calculations, and display the results on-line. To obtain throughput times of 1 min, computation time must be approximately 10 sec in order to leave time for comparison and output.

To define computer requirements for the addition of steady-state and transient math models to the ETF and PWT on-line capability, selected existing models were obtained and executed off-line on the AEDC IBM 360/50H central computer. Most programs required overlay to execute within the present 65,536-word core memory. Computer core memory size requirements and throughput times were recorded for off-line operation. Graphics display software and analysis program core memory requirements were also determined. This was done separately as the present IBM 360/50H was not large enough to perform all operations simultaneously, as will be required for on-line usage. These results, when compared with similar results from the engine manufacturer's and the AFAPL computer systems, are used to estimate computer requirements for the on-line addition of present and near-future mathematical models. Because of the inherent differences in computer system hardware and software, the only positive method of determining the suitability of a proposed computer system for processing math models is to execute a selected "benchmark" sample of models on a proposed computer system and thereby determine core memory requirements and throughput times.

There are several indicators of the power and efficiency of a computer system, such as memory cycle time, add time, multiply time, divide time, read/write time, compile time, and peripheral device characteristics and availability. It is difficult, at best, to select one (or more) of the system characteristics which will serve as an independent variable against which to evaluate throughput time parameters. From the results of this investigation, it appears that memory cycle times may be used, cautiously, as an independent parameter for evaluating the results of the transient model investigation. Generally, the large-scale third-generation computers now in use by most agencies have memory cycle times on the order of 1 to 2 μsec, whereas the previous (second) generation systems had memory cycle times on the order of 2 to 6 μsec. In addition, software characteristics and input/output functions have been greatly improved in both flexibility and speed, and several new concepts have been introduced which make interfacing of engineer and computer a practical reality. One such interactive device is computer graphics which was also investigated simultaneously with this project.

3.1 STEADY-STATE ENGINE MATH MODELS

Several engine steady-state performance simulation models were obtained and executed at AEDC, and several more programs were discussed with engine manufacturers to determine memory size and throughput time requirements. The major results of this investigation are shown in Fig. 7. High-speed core memory requirements as a function of math model are shown in Fig. 7a. Large-scale computer memories are normally available in discrete increments of approximately 32, 000 words. The approximate 18, 000-word requirement for use by the AEDC IBM 360/50 system supervisory or operating system (OS) and the approximate 50, 000-word requirement for graphics software and comparison programs are shown superimposed on the math model-only requirements.

On-line core memory requirements for the steady-state (S) and combined steady-state and transient (C) models evaluated at AEDC ranged from approximately 100, 000 to 114, 000 words. Other applicable models which may be utilized at AEDC ranged up to approximately 120, 000 words. Throughput times for these models are shown in Fig. 7b and ranged from approximately 12 to 23 sec/point for those models evaluated at AEDC using memory overlay and from 5 to 12 sec/point for the other applicable programs not requiring memory overlay. The nonoverlay times will probably satisfy the ETF and PWT on-line data turnaround target time requirement. Computer memory overlay is a technique of repeatedly using the same blocks of memory during different stages of a calculation process, resulting in increased computation time.

3.2 TRANSIENT ENGINE MATH MODELS

Several transient performance simulation models (T) were obtained and executed at AEDC, and several more models were discussed with engine manufacturers. Core memory requirements for these models were approximately equal to those of the steady-state models investigated. Memory size requirements with computer overlay ranged from approximately 100, 000 to 120, 000 words, as shown in Fig. 8a. Throughput time requirements for these overlayed models (non-overlayed models require approximately 20 percent more core memory) are shown in Fig. 8b and ranged from approximately 10 to 105 sec/sec ratio of computer-to-real time for the AEDC IBM 360/50H computer, for a nominal transient calculation time increment (t_c) of 10 msec.

Throughput time requirements for the transient models evaluated varied greatly as a function of computer speed and calculation time

increment as shown in Fig. 9. Calculation time increment and computer memory cycle time, for three different computers, make a significant difference for a given transient program (T_3) where computer-to-real time ratios ranged from 10 to 39 sec/sec for memory cycle time $t_m = 0.75\ \mu sec$, 39 to 115 sec/sec for $t_m = 2\ \mu sec$, and 112 to 231 sec/sec for $t_m = 4.8\ \mu sec$ as the calculation time increment (t_c) was decreased from 20 to 5 msec. The method of programming also makes a significant difference (Fig. 9b) since, for the IBM 360/50H, the ratio of computer-to-real time varied from 39 to 115 for program T_3 and from 79 to 198 for program T_4 as t_c was decreased from 20 to 5 msec.

A modest reduction in core memory requirement may be realized by utilizing a computer system with word lengths in excess of 32 bits. For example, the AEDC CDC 1604B system ($t_m = 4.8\ \mu sec$) used during the transient execution time requirement investigation (Fig. 9a) required approximately 32, 000, 48-bit words (maximum available) to execute a transient program (math model-only) which required approximately 40, 000, 32-bit words on the 360/50H system. From other such direct comparisons available to some engine manufacturers, there is an approximate 20-percent memory requirement reduction available on such a system.

3.3 DYNAMIC MATH MODELS

Although dynamic models will be the subject of the Phase II investigation, one dynamic simulation program was obtained and executed at AEDC during the present investigation. This model was a stage-by-stage dynamic representation of a fan/compressor mounted on a common spool with separate nozzle closures at the fan and compressor exits to vary the back pressure on the system. The purpose of such a simulation program is to predict operating line shifts and stalls caused by time variant distortion, as validated with compressor rig test data. This model is reported in Ref. 5, Part VIA.

The on-line core memory requirement for using this model with graphics display is approximately 98, 000 words. The computer-to-real time ratio is shown in Fig. 10 and ranged from approximately 13, 000 to 20, 000 sec/sec as the calculation time increment was decreased from 1 to 0. 1 msec on the AEDC IBM 360/50H computer system. This time ratio is much too great for on-line usage, which will require an increase in throughput time by a factor of approximately 30 to compute and display 0. 1 sec of dynamic test data within the 1-min target time established earlier. Perhaps analog or hybrid computers will be required to accomplish this feat.

There are several other types of dynamic models available which are larger than this one, and possibilities of including such a simulation within the total engine models discussed previously are under consideration.

3.4 INTERACTIVE GRAPHICS

An interactive computer graphics display terminal installation was utilized and studied simultaneously with the present investigation to evaluate the interface between analysis engineer and computer while reviewing both test and math model data. Several of the steady-state and transient engine math models studied at AEDC had built-in graphics interface routines which transferred the computer results to the graphics display terminal access areas on supplemental or disc pack memory devices. From these areas, the math model data, as well as the test data, were displayed and directly compared on the graphics display from which the desired print-outs and hard-copy plots were requested. This combination of man and machine was found to be highly valuable in obtaining more timely and meaningful test results and in reducing significantly the man-hours required for data analysis.

The interfacing routines contained within the steady-state and transient models investigated during this study required approximately 2000 to 4000 words of core memory. However, the graphics software routines needed to acquire, process, and display data required approximately 40, 000 words of core memory on the IBM 360/50. Other such graphics software available with more flexibility and optional features is known to require approximately 60, 000 words. The IBM 360/50 computer system internal speed was sufficient to produce a rapid graphics display response when using preprocessed test and math model data. Preprocessed information will be of little benefit during on-line testing, as compared with immediate math model processing using "live" test data inputs.

SECTION IV
FUTURE COMPUTER REQUIREMENTS

Future propulsion system math model requirements for steady-state, transient, and combined inlet/engine performance at AEDC have been extrapolated for an approximate 4-yr period. These requirements are dictated primarily by projected test requirements for the new major weapons systems under development at this time.

4.1 STEADY-STATE MODELS

The future steady-state math models will most likely include more precise representations of all major engine components, which will require more core memory than previous models. It is expected that memory requirements for near-future steady-state models will be approximately 130, 000 words. There is a trend toward combining steady-state and transient engine math models so that the steady-state result is merely a special case of the more general transient math model computer requirements for combined models as discussed below.

4.2 TRANSIENT MODELS

The future transient math models will include more detailed representations of all engine control components and their interactions with each other and with the engine itself, which will necessitate more core memory and faster throughput times for on-line usage than the present models require. It is expected that memory requirements for near-future transient and combined steady-state/transient models will be approximately 150, 000 words. Throughput rate for the transient and combined programs must be about four times that of the present AEDC 360/50H computer system in order to obtain computer-to-real time ratios of approximately 5 sec/sec to satisfy the test facility on-line data turnaround target time.

4.3 DYNAMIC ENGINE MATH MODELS

It is very difficult to determine future dynamic math model requirements since this type of simulation is relatively new and nonstandard as compared with the steady-state and transient engine math models. If the dynamic engine math model comes into more general use in the future, analog or hybrid computers may be required to satisfy on-line turnaround requirements. These requirements will be more fully determined during Phase II of this study.

4.4 INLET/ENGINE COMBINED MODELS

Future requirement goals must include inlet/engine steady-state and transient math models. Although little investigation of these models has been conducted under the present study, it is already evident that the entire propulsion system must be simulated and tested before commitment of hardware. Some currently known inlet/engine programs

require approximately 150, 000 words. Future inlet/engine math models will probably require up to 200, 000 words. These requirements will be further defined during Phase II of this study.

SECTION V
CONCLUSIONS

Present and near-future requirements for digital computer simulation of gas turbine engine steady-state and transient performance were defined. Some preliminary requirements were also determined for dynamic engine simulation and inlet/engine combined mathematical models. The results of this investigation are summarized as follows:

1. Present and near-future steady-state and transient engine math models will require approximately 150, 000 words of dedicated core memory capacity, including the capability to utilize an operating system and support on-line graphics analysis equipment.

2. Computer memory cycle times on the order of 0.5 μsec will be required to provide on-line display of steady-state and transient math model results and comparisons with test data in real times which will keep pace with testing rate requirements.

3. One dynamic compressor model evaluated required approximately 98, 000 words of core memory, including operating system and graphics software. Very fast throughput rates will be required to satisfy on-line testing requirements; analog simulation methods may be required.

4. It is estimated that inlet/engine combined math models will require approximately 200, 000 words of core memory. Thoughput rates must be about ten times as great as for the engine-only math models in order to accomplish balance between the inlet and engine components and controls.

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APPENDIX
ILLUSTRATIONS

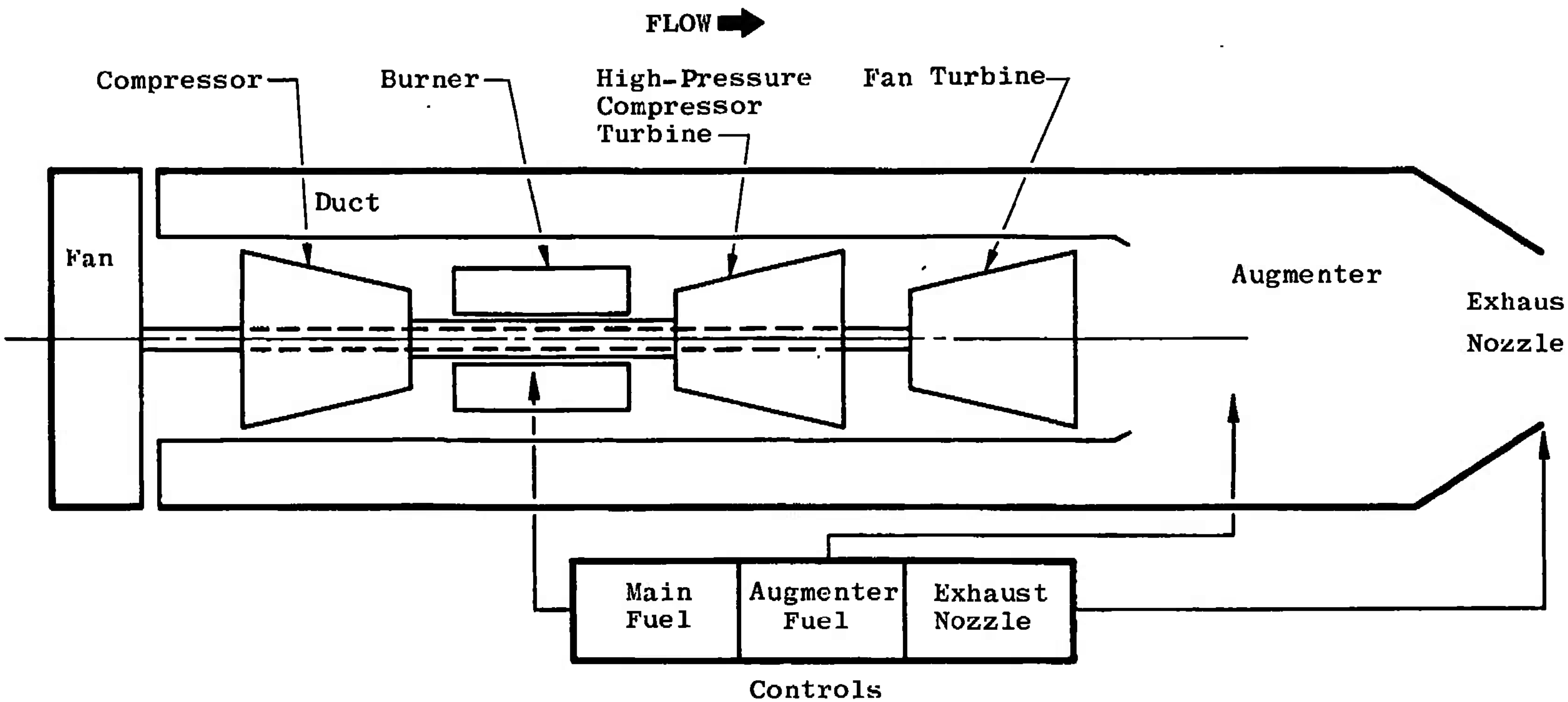


Fig. 1 Block Diagram of Typical Mixed-Flow Turbofan Engine

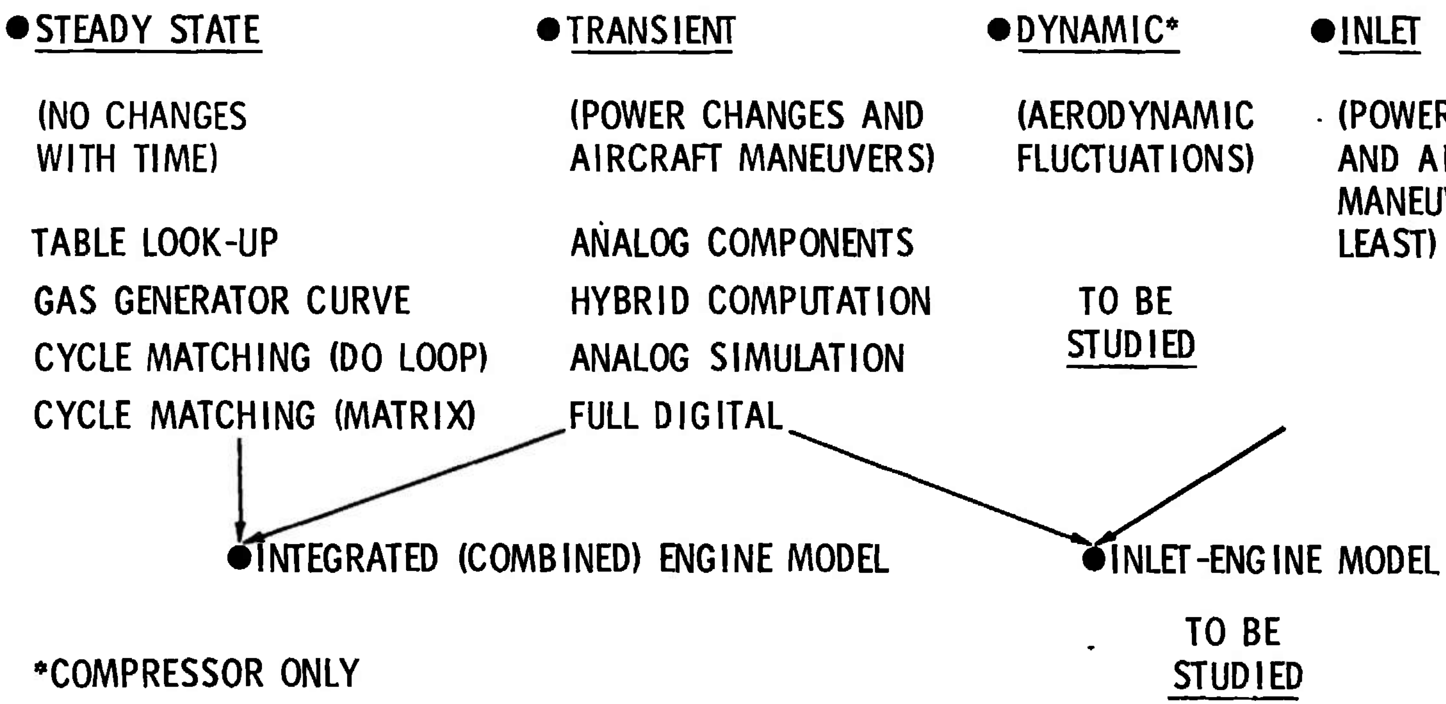


Fig. 2 Propulsion System Math Models

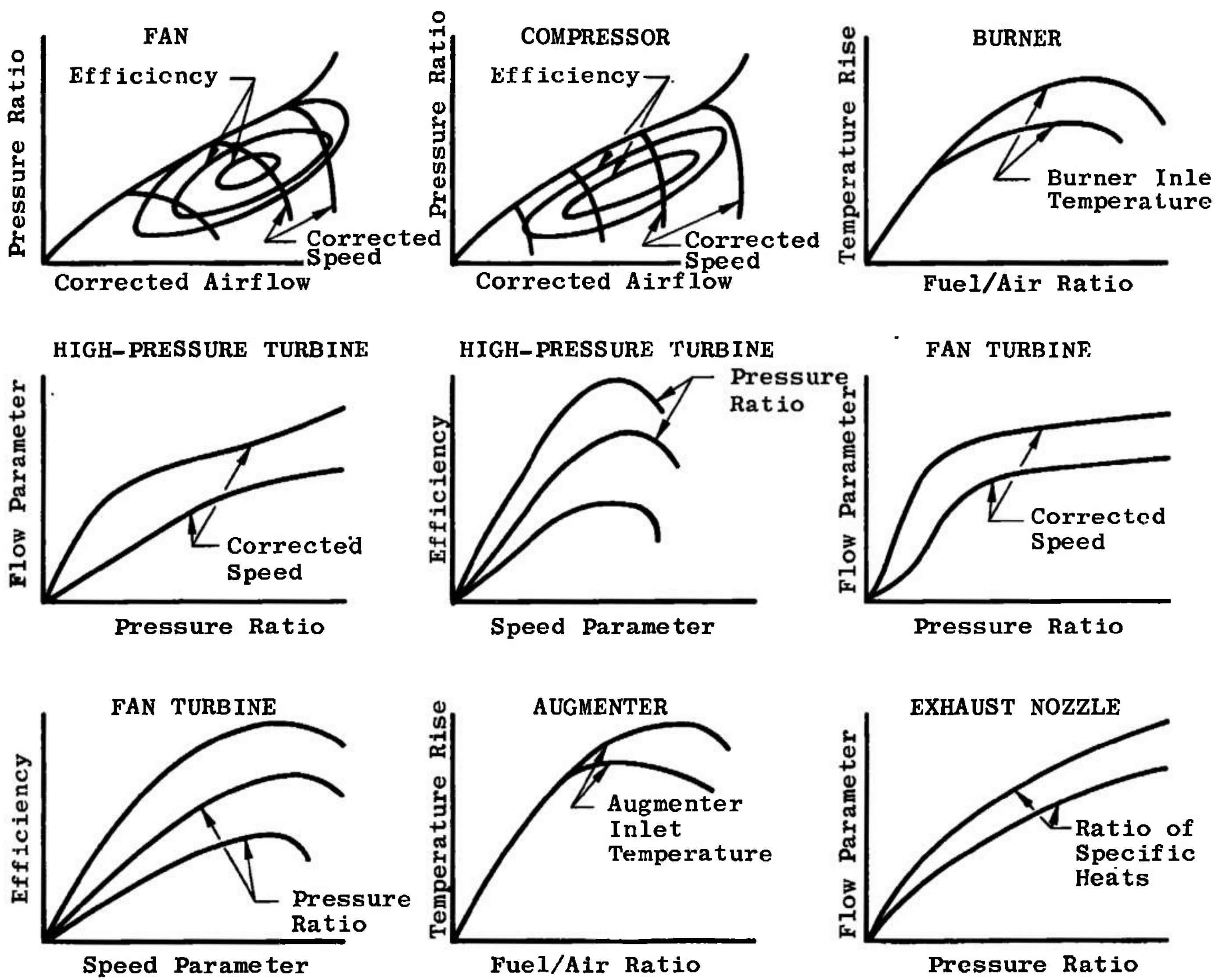
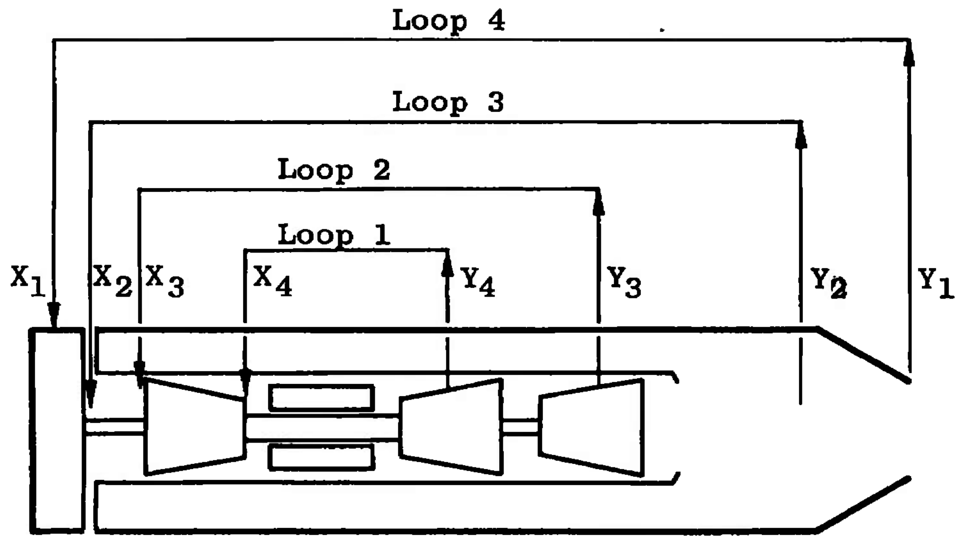
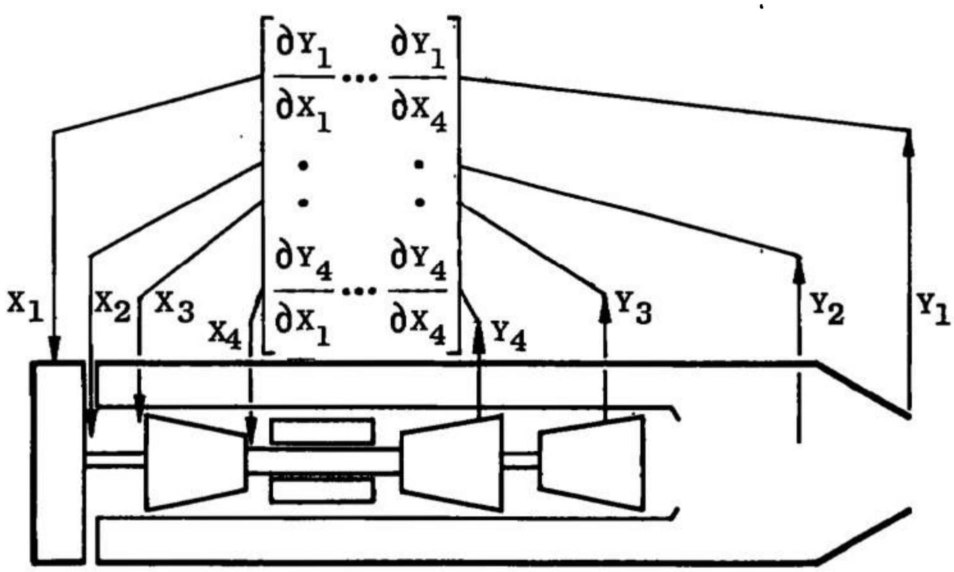


Fig. 3 Typical Component Maps Used for Turbofan Math Model



Loops Vary X_i to Reduce Y_i Errors

a. Nested Loop



Matrix Solution Recommends Increments for X_i to Reduce Y_i Errors

b. Simulation of Turbofan Engine (SMOTE)

Fig. 4 Cycle-Matching Balance Techniques

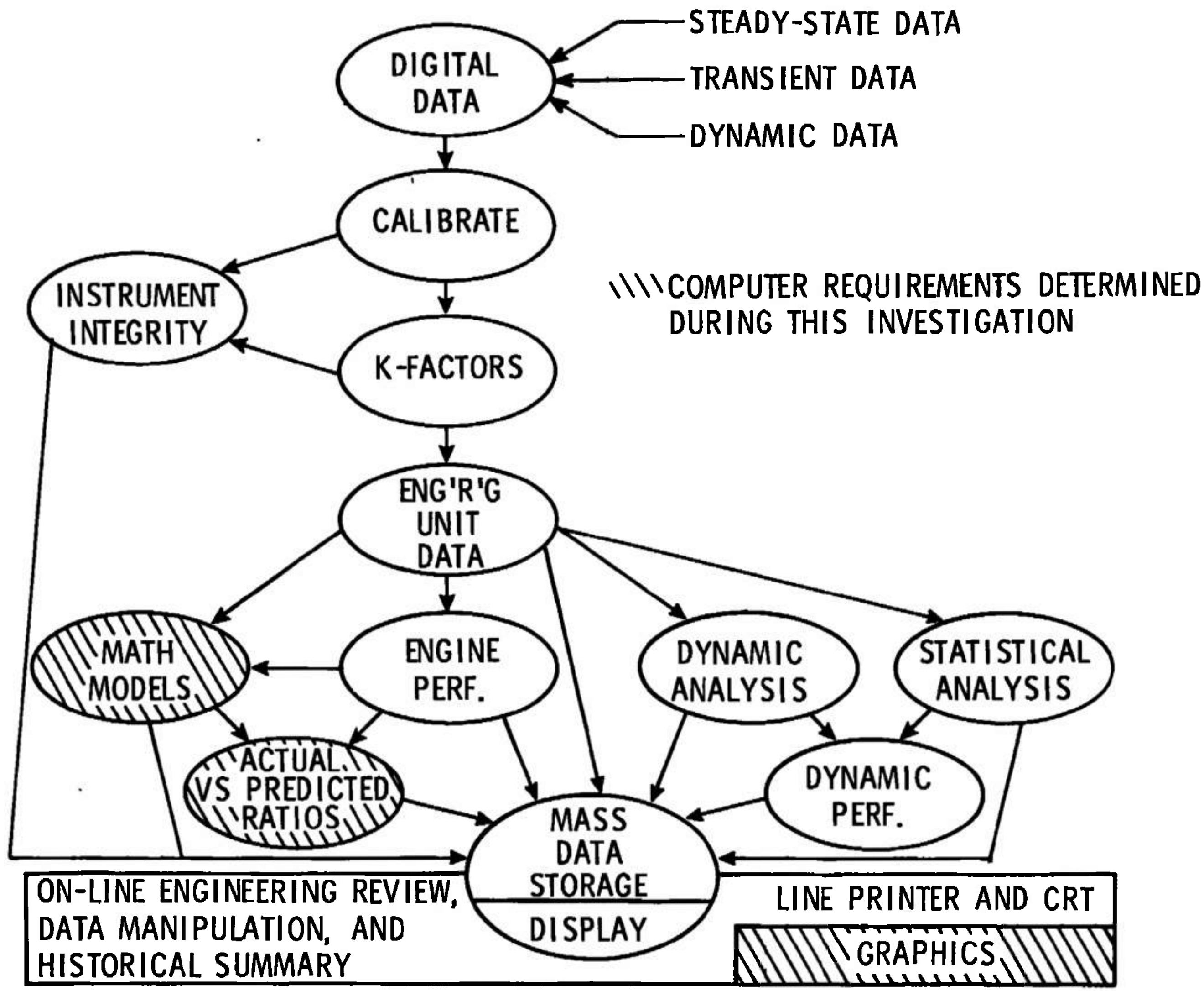
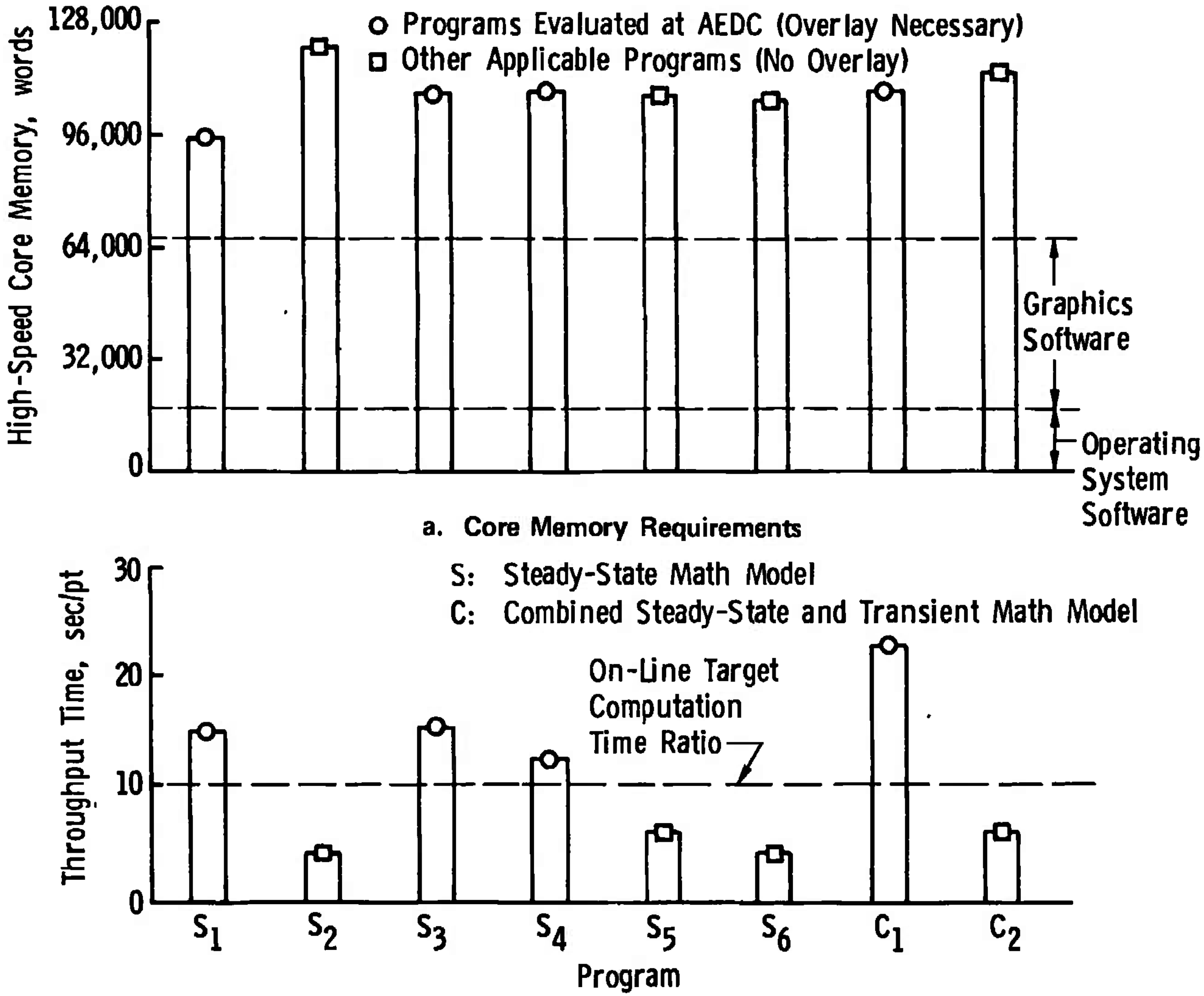


Fig. 5 Engine Test Facility and Propulsion Wind Tunnel Facility On-Line Digital Data Flow Chart

EVENT		TIME	
● DATA ACQUISITION CYCLE		0.5 to 2 MIN	TARGET TIME <5 MIN
● RETURN ON-LINE DATA			
ACTUAL PERFORMANCE PRINT MATH MODEL RESULTS PRINT	SIMULTANEOUS PROCESSING	1 MIN	
COMPARISON OF ACTUAL VS MATH MODEL PRINT		1 MIN	
SIGNIFICANT CURVES CRT HISTORICAL SUMMARY PRINT	SIMULTANEOUS DISPLAY	1 MIN	

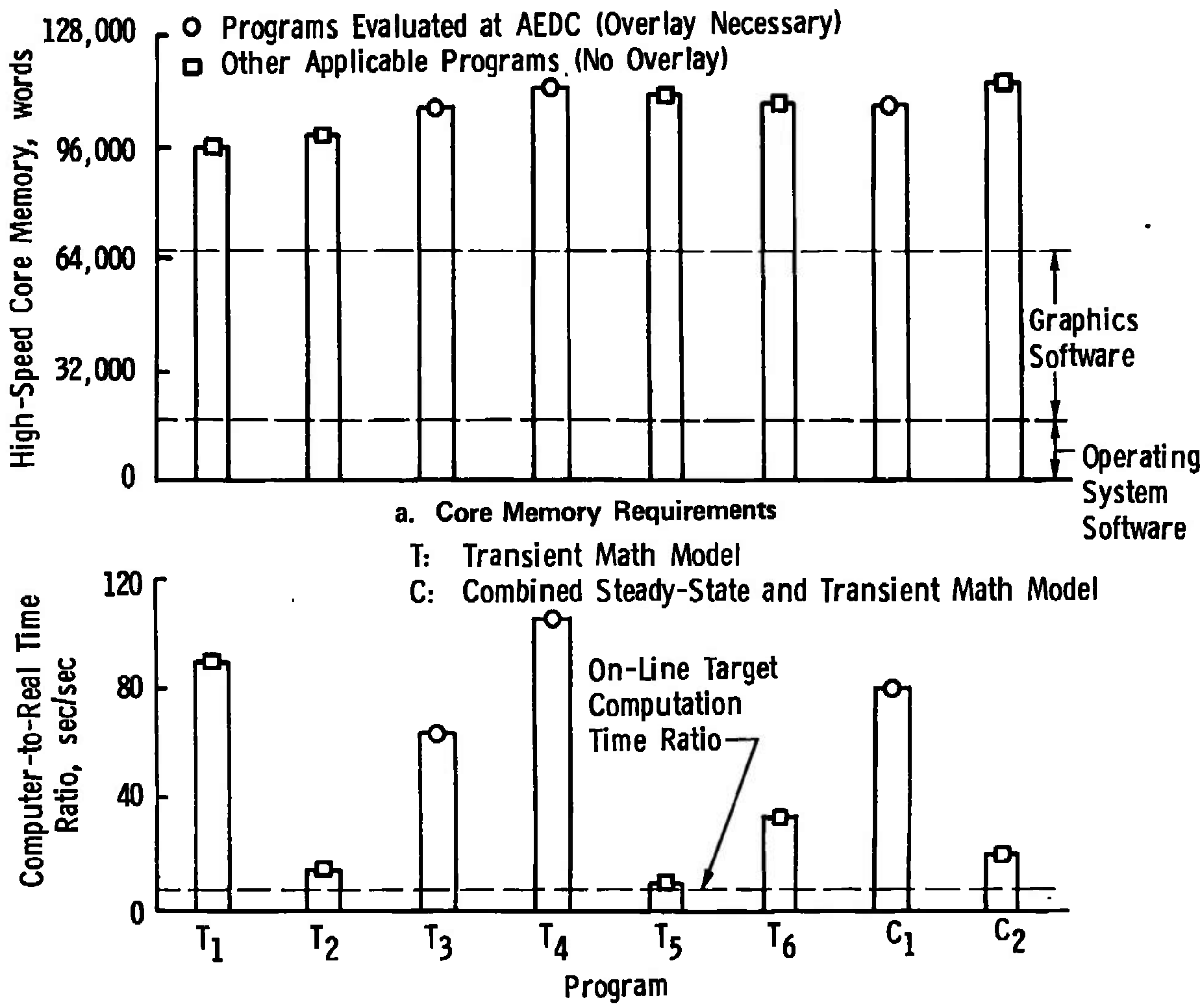
Fig. 6 Engine Test Facility and Propulsion Wind Tunnel Facility Target On-Line Data Turnaround Time



a. Core Memory Requirements

b. Throughput Time for IBM 360/50

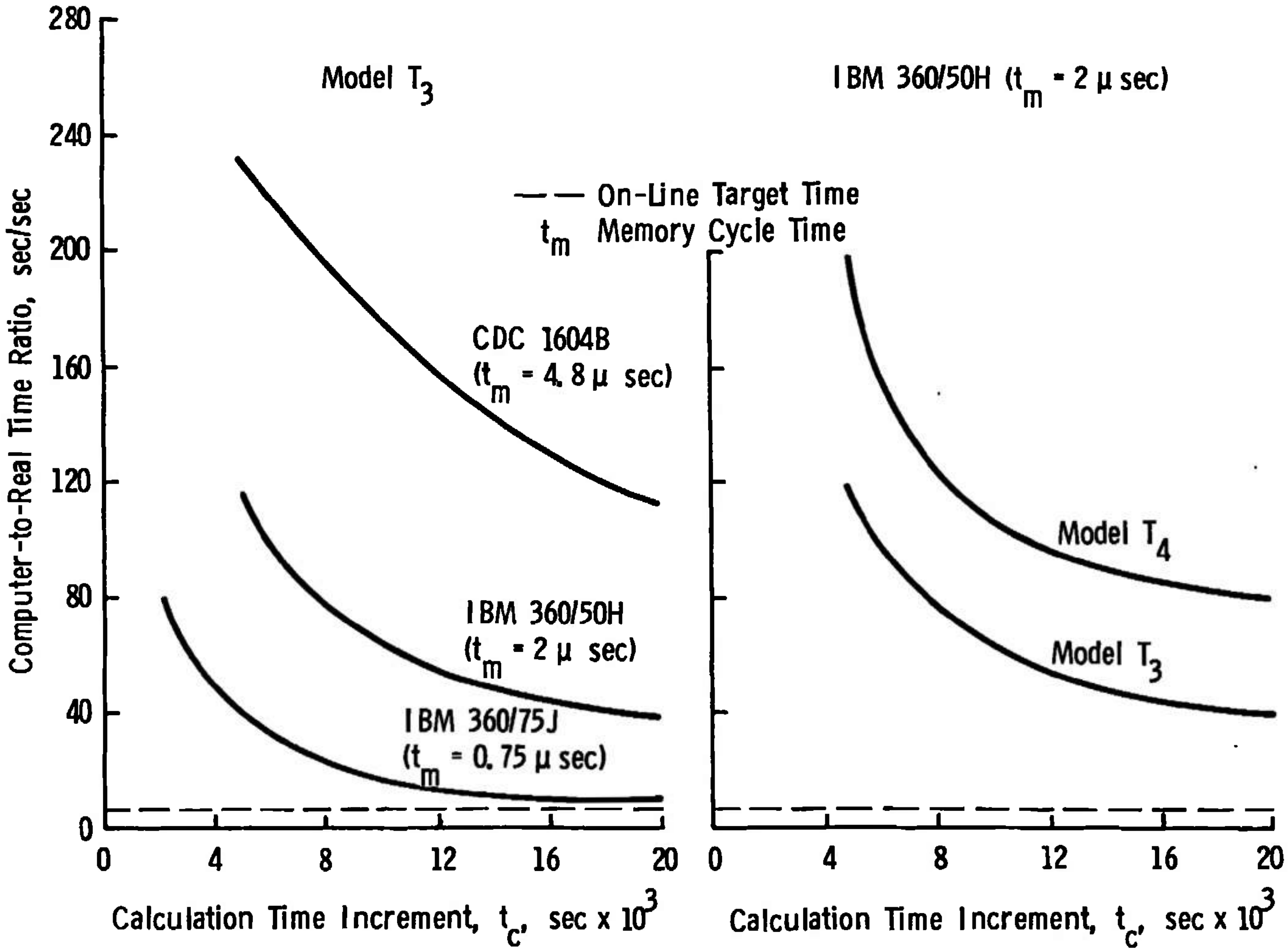
Fig. 7 Steady-State Engine Math Model Requirements



a. Core Memory Requirements

b. Throughput Time Requirements for Calculation Time Increment (t_c), 10 msec for IBM 360/50

Fig. 8 Transient Engine Math Model Requirements



a. For Various Computers

b. For Two Math Models of Same Engine

Fig. 9 Transient Engine Math Model Throughput Time Requirements

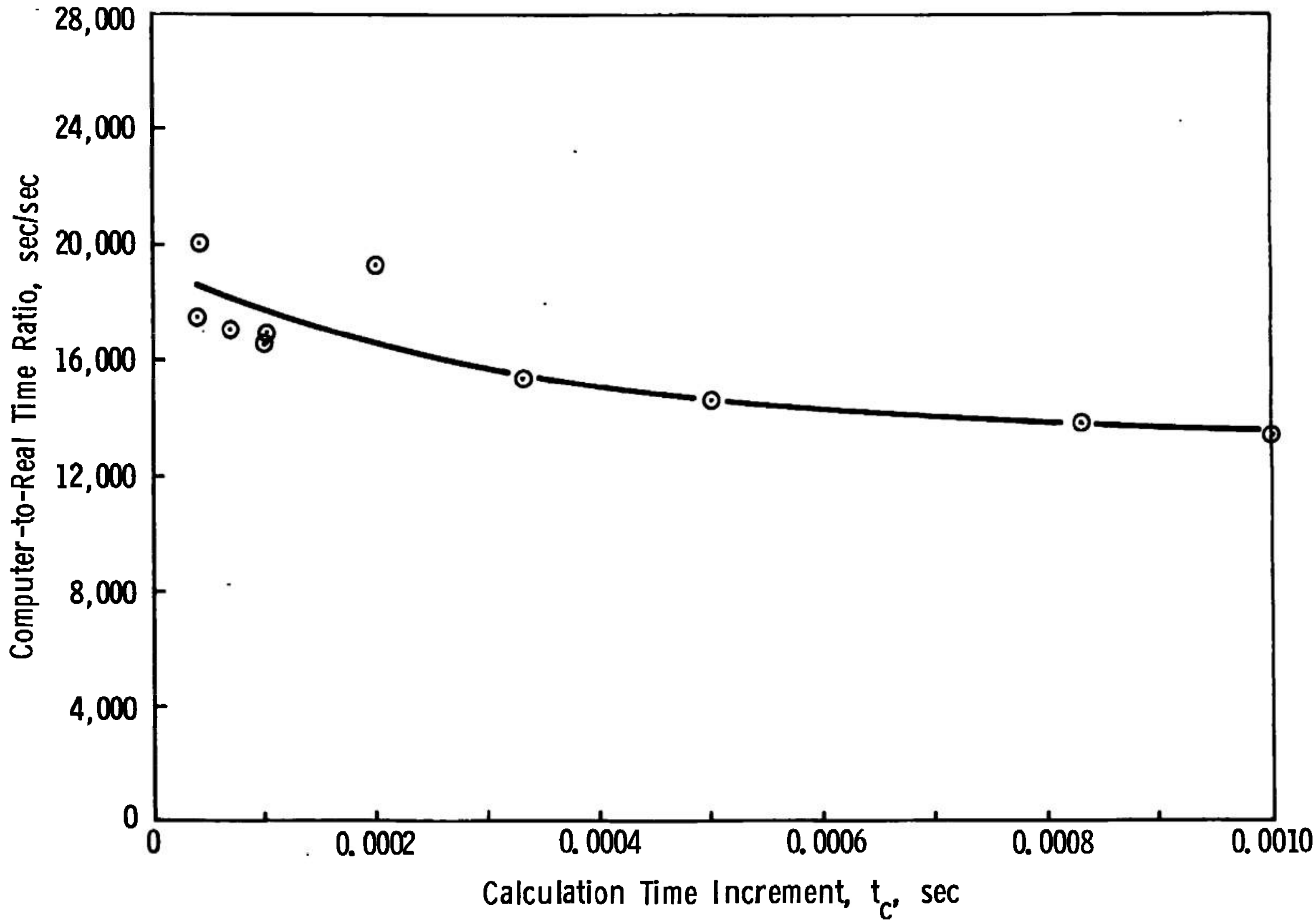


Fig. 10 Dynamic Compressor Math Model Throughput Time Requirement for IBM 360/50

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13. ABSTRACT

Present and near-future requirements for the addition of digital computer simulation of gas turbine engine steady-state and transient performance to the present Engine Test Facility and Propulsion Wind Tunnel Facility digital data capability were determined based on information and guidance provided by the Air Force Aero Propulsion Laboratory and various gas turbine engine manufacturers. During Phase I of this study, digital computer high-speed core memory size and throughput times were determined and are presented for several modern steady-state and transient mathematical model simulation programs. Display requirements were also determined and are presented for full utilization of the mathematical model results, off-line and on-line. Some preliminary results on dynamic compressor mathematical models are discussed.

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test facilities						
altitude simulation						
computerized simulation						
digital simulation						
jet propulsion						
jet engines						
turbofan engines						
turbojet engines						
graphical analysis						
graphics						